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Modelling of femur fracture using finite element procedures

Miguel Marco[a,*], Eugenio Giner[b], Ricardo Larraínzar-Garijo[c], José Ramón Caeiro[d], María Henar Miguélez[a]

[a] Department of Mechanical Engineering, Universidad Carlos III de Madrid, Avda de la Universidad 30, 28911 Leganés, Madrid, Spain
[b] Center of Research in Mechanical Engineering – CIIM, Department of Mechanical and Materials Engineering, Universitat Politècnica de València, Camino de Vera s/n, 46022 Valencia, Spain
[c] Orthopedics and Trauma Department, Hospital Universitario Infanta Leonor, Surgery Department, Universidad Complutense Madrid, C/ Gran Vía del Este, 80, 28031 Madrid, Spain
[d] Orthopedic Surgery and Traumatology Service, Complejo Hospitalario Universitario de Santiago de Compostela, Rúa de Ramón Baltar, s/n, 15706 Santiago de Compostela, A Coruña, Spain

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ABSTRACT

During the last decades human femur fracture has been mainly analysed using an experimental approach focused on cadaveric or synthetic bones. Nowadays, advances in computational technologies allow using numerical methods, such as the finite element method for femur fracture analysis. However, fracture morphology has been scarcely studied using numerical methods despite the interest of this study due to the different clinical treatment required for each fracture type. In this work, different fracture modelling techniques have been analysed with the objective of predicting a realistic fracture path, which in the literature is often limited to the initial steps of fracture. The main goal of this article is to compare different numerical approaches and to provide a robust methodology for femur fracture simulation. Experimental work was carried out on a synthetic femur in order to validate the numerical models. Through this validation we verified that some numerical methods present convergence problems, and they are not useful to model long crack paths. The best results are obtained by simulating the crack growth by a local material property degradation applied through successive analyses. This technique has been applied to a real human femur, obtaining accurate results in fracture morphology prediction.

1. Introduction

Femur fracture is a common traumatism affecting a large number of patients in the world mainly due to the aging population. These traumatisms usually lead to long recovery times, disability or even post-surgery mortality [1], besides the social cost also involved. Approximately 1.6 million hip fractures occurred worldwide in the year 2000 [2], while in 2007 approximately 281,000 hospitalizations were registered in the United States due to hip fracture [3]. Mortality rates at 1 year following hip fracture were approximately 22% for men and 14% for women in 2005 [4]. Approximately 90% of these fractures are the result of a fall [5]. Moreover diseases such as osteoporosis predispose a person to an increased risk of hip fracture [6].

The human femur has been extensively analysed through *in vitro* experiments in literature in order to understand its mechanical behaviour related to fracture. These experiments have provided a great knowledge of mechanical behaviour of femur, fracture loading and fracture morphology. Experimental tests evidenced that the femur behaves linearly elastic up to failure when physiological loading conditions are applied [7–9]. This idea is also corroborated by Cristofolini *et al.* in [10] stating that linearity holds up

* Corresponding author.
E-mail address: mimarcoe@ing.uc3m.es (M. Marco).

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Nomenclature

List of Symbols

ρ	density
ν	Poisson's ratio
E	Young's modulus
ε_c	failure strain
G_c	critical energy release rate
K_c	fracture toughness
E_0	initial Young's modulus
HU	Hounsfield units
t	time
ρ_{QCT}	radiological density
ρ_{ash}	ash density
ρ_{app}	apparent density
σ_{crit}	critical stress
$\sigma_{max,ppal}$	maximum principal stress

to the last stages of the loading path, close to the onset of fracture.

Despite the need of experiments, numerical models can also help in the understanding of femur behaviour under different load cases. In this regard, numerical models provide a useful way to understand the fracture process and, eventually, help in the assessment of fracture risk based on image diagnostics. Numerical modelling of bone fracture is a difficult task, because of the bone heterogeneity and the influence of mechanical properties of bone. It is worth noting that accurate predictions strongly depend on a realistic bone behaviour characterization. There is a wide dispersion about numerical values of bone mechanical properties in literature, due to changes in terms of age, disease, nutrition and other factors [11–13]. The dependence of the fracture load with these parameters was studied by Marco et al. in [14].

Advances in computer modelling allow the analysis of bone fracture, both at micro- and macroscale [15]. Proximal femur is the most interesting area in human femur since hip fracture commonly occurs at this zone. Linear finite element models have been successfully applied to the prediction of the elastic response and the fracture load of a human femur, with a correlation of about 90% [16].

The artificial, or composite femur (as usually denoted), has been commonly used in the literature as a simulant of real bone. It is important to emphasise that this kind of specimens is designed to simulate the biomechanical properties of young and healthy femurs [17–19]. These similarities were tested by means of axial compression, bending and torsion tests through the measurement of the corresponding stiffness and ultimate failure strength [17,18]. The use of artificial bone provides advantages for model validation avoiding the variability of properties inherent to biological tissues [18]. Composite bones are useful to develop controlled analysis, due to their homogeneous properties in two distinct zones, smoothed surface and low variability between specimens [18]. The failure modes of these composite models are close to published findings for human bones [18]. This composite femurs are useful in some clinical tasks, such as the test of a screw fixed to it [20,21] or the behaviour of the bone after a repair through an implant or prosthesis [22,23]. Prostheses for femur fracture have been analysed experimentally in literature joined to synthetic specimens [24].

Cristofolini et al. presented a deep analysis of the synergy between experimental test and numerical models in the study of the human femur [25]. Numerical models have also been used to obtain strain values before and after a femur fracture is repaired [22,23], and have been compared with recent measurements techniques (such as DIC, [26]) in terms of strains on the surface of the bone. These models are based on previous computed tomography (CT-scan), and they commonly analyse the stance loading of the human femur [10,7,27]. Using numerical methods and experimental tests has enabled to check the linear behaviour of the femur under physiological loading conditions [7] and its fracture load or global stiffness [25,27].

Despite the efforts on the simulation of human femur behaviour, fracture paths have been rarely modelled using numerical approaches. Some works have focused on the fracture simulation at the proximal area, most of them obtaining small fracture paths [14,27] through the XFEM method. Degradation of mechanical properties has been applied to the fracture modelling of human femur [28,29], predicting more realistic and longer fracture paths.

The main goal of this work is the analysis of different approaches to model the fracture propagation in the proximal zone of the femur. These techniques are: eXtended Finite Element Method (XFEM), material property degradation at element level, element deletion and other variants with incremental crack growth. Validation was carried out using a human bone simulant (synthetic femur) because of the simplicity of this femur (composed only by two homogeneous materials representing trabecular and cortical bone) and also with application to a real human femur. The final objective of the work is to develop a technique able to model realistic fracture paths, since simulation of long fracture paths can be useful in order to predict different fracture morphologies in human femur. Once the method was validated, it has been applied to simulate other loading configurations and bone mechanical properties, including degradation of properties due to bone pathologies. There is a lack of works focused on the comparison of different numerical modelling techniques for fracture simulation in biomechanical applications. In addition, works in the literature only simulate the initial steps of fracture. It is important to establish a numerical technique able to accurately predict long fracture paths, since the further treatment strongly depends on fracture morphology.

2. Materials and methods

The experimental work and numerical model validation on a bone simulant is detailed in a previous work of the authors [14]. We focused on testing a synthetic bone under different loading conditions. Firstly, the femur was loaded in the elastic regime and finally the load was increased up to femur fracture. In [14], the numerical model was validated both in the elastic regime and in terms of fracture load comparing with experimental results, showing reasonably accuracy. The numerical procedure in [14] just involved the XFEM method as available in the commercial code Abaqus, being able to simulate only the onset of the fracture. The main motivation